RESEARCH DEPARTMENT

Measurement of the ratios of the currents flowing in the elements of a v.h.f. transmitting aerial

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SUMMARY

With the growth of the BBC television and v.h.f. sound services some transmitting aerials must of necessity comply with increasingly complex requirements in respect of the shape of the horizontal radiation pattern. It is difficult, however, to make satisfactory measurements of this pattern on the final aerial. In order to ensure that specified requirements are met, it is therefore necessary to measure the radiation pattern of a small-scale model of the aerial, and then to check that the ratios of the currents flowing in different parts of the final aerial are the same as for the model. Two methods of carrying out such measurements are described and compared.

1. INTRODUCTION

Because of the restricted number of available channels, the BBC plan for national cover of its Band I television and Band II v.h.f. sound services involves the use of many stations operating on the same channel. In order to minimize co-channel interference the earlier stations are geographically separated as far apart as practicable; in the case of television stations offset carrier frequencies and different polarizations are also used to achieve additional protection. As the plan develops, however, adequate protection cannot be achieved by these measures alone; it is consequently necessary to control the horizontal radiation patterns (h.r.p.s) of many of the new stations within closely prescribed limits. This is also desirable in order to provide the best possible cover to the densely-populated areas, with a limited transmitter power.

The more demanding the requirement the more important does it become to ensure that the prescribed h.r.p. is achieved, but it is difficult to make satisfactory measurements on the final aerial. It is therefore necessary to measure the radiation pattern of a small-scale model of the aerial, and then to check that the ratios of the currents flowing in different parts of the full-scale aerial conform to those in the model. Small errors in these ratios may result in large deviations from the required h.r.p. This report describes two methods of measuring such current ratios; they have been developed with particular reference to the type of transmitting aerial used by the BBC, which is described in Section 2.

2. BBC AERIAL-DESIGN TECHNIQUE

2.1. General

In general, aerials for television and v.h.f. sound broadcasting used by the BBC comprise rings of radiating elements (usually $\lambda/2$ dipoles or radial unipoles) arranged round a support mast. To obtain directivity in the vertical plane, a number of such rings (or tiers) are spaced vertically along the mast column.

Most of the v.h.f. stations already in service are provided with aerials of identical symmetrical tiers, with elements carrying equal-amplitude currents having a simple phase relationship. In any one tier every element is then subjected to identical mutual-impedance effects from the other elements. Thus the elements in the driven array remain similar to one another as regards their effective input impedance, provided they are of the same physical form and dimensions. In such cases there is no great difficulty in ensuring that the radiating currents in the elements are correct in amplitude and phase, so that the h.r.p. corresponds closely in practice to that predicted from the aerial geometry.

In order to obtain more directional h.r.p.s it is necessary to resort to aerial systems having dissimilar tiers, or elements carrying currents of unequal amplitudes, or a combination of these features. Sometimes a particular phase relationship between radiating currents in elements on different radial bearings is specified. The difficulty with these systems is that the effect of mutual coupling may result in the elements having widely differing impedances. As a result, it is not easy to ensure that the specified performance of the aerial is obtained.

2.2. Design Procedure

The design procedure adopted for aerials conforming to exacting h.r.p. requirements is to consider possible systems in the following order of increasing complexity:

(a) Equal currents, either in phase or in antiphase, in all the elements; all tiers identical.

(b) Equal currents either in phase, or in antiphase, in all the elements; tiers dissimilar, in order to simulate similar tiers with unequal currents in the elements.

(c) Unequal currents, either in phase or in antiphase, in the elements of each tier; all tiers identical.

(d) As (c) but tiers dissimilar.

(e) The preceding possibilities, but with other phase relationships between currents in the elements of each tier.

Having decided from theoretical considerations the form of aerial system giving a good approximation to the required performance, it is necessary to carry out measurements to determine the precise shape of the h.r.p., because the theoretical

predictions involve certain assumptions.[1] They do not, for instance, include the effects of re-radiation from support structures and stay wires. In view of the large size of aerials for Bands I and II it is not practicable to carry out development work on a full-scale aerial; measurements are therefore made on a small-scale model of the basic features of the proposed system.

2.3. Small-Scale Technique

The models of aerials for Bands I and II are built to a scale factor of about 10 : 1, giving an operating frequency in the range 450 to 1000 Mc/s.

For aerial systems having identical tiers it is usually sufficient to measure the h.r.p. of a single tier, since the h.r.p.s of all tiers are the same. One exception is a vertically-polarized aerial system mounted on a stayed mast; in this case re-radiation from the stay wires affects the h.r.p. of each tier differently, and it may therefore be necessary to measure the h.r.p. of the complete aerial system.

For an aerial in which the tiers are dissimilar, two methods of measurement of the complete h.r.p. are possible:

(a) The complex h.r.p.s of individual elements are measured,[2] and the h.r.p. of the complete aerial is then calculated by appropriate addition of the patterns.

(b) A representative part of the aerial is made and the complete h.r.p. measured directly.

In general, method (a) is the more time-consuming, in spite of the greater complication of the model required for method (b). Method (a) would be extremely laborious if it were necessary to investigate the effects of changes to the aerial dimensions in order to achieve a satisfactory h.r.p.

Method (b) requires that the model be provided with means whereby the radiating elements can be driven with the specified currents, and a check of these currents must be possible. Having established the correct currents, the complete h.r.p. is measured directly; in most cases it is then possible to make small changes to the aerial configuration to achieve the optimum h.r.p. without unduly altering the radiating currents.

In view of its greater accuracy and speed, (b) is the preferred method in the BBC.

2.4. Full-Scale Technique

It is not generally convenient to measure the h.r.p. of a Band I or Band II aerial directly during the initial setting up at a contractor's works. The main difficulty is that a large flat area, free from obstructions likely to cause reflexions, is required in order to make accurate measurements. A further difficulty is that since the aerials may be of the order of 100 ft (30 m) in height and weigh many tons it is not convenient to rotate the aerial on a turntable as in the case of model aerials. Moreover, if the h.r.p. were measured and found to be insufficiently near to that predicted, it may not be apparent what adjustments are required to achieve the correct h.r.p.

Since the structural form of the aerial corresponds to that of the small-scale model used for the basic aerial design, an incorrect h.r.p. can only result from incorrect currents in the aerial elements. It is therefore possible to ensure that the full-scale aerial will have the required h.r.p. by checking that the relative amplitudes and phases of the currents conform to the specified values. As the h.r.p. requirements have become more demanding it was considered desirable to develop a method of measuring these current ratios.

3. METHODS OF MEASURING CURRENT RATIOS

3.1. General

The component of current with which we are concerned is that which contributes to the radiated field; it will be henceforth called the 'radiating current'. It should be noted that the radiating current may be different from the current flowing in a particular limb of the radiating element. In a folded dipole, for instance, the radiating current is the vector sum of the currents flowing in all of the limbs. In this case the current in an individual limb includes a component of current whose effect on the distant field is cancelled by opposing components flowing in other limbs of the dipole.

Again, one method of energizing the separate elements of an aerial with equal co-phased or antiphased currents is to drive the aerials from a common point through feed lines which are an odd integral number of quarter-wavelengths in length; this method equalizes the *input* current to the aerial terminals, even though the elements have different impedances. If, however, there is a reactance-compensating circuit connected across the aerial drive-point, the current in this reactance is included in the equalized input currents.* Although the elements of the aerial system may all be mechanically identical, the effects of mutual coupling cause the drive-point impedance to depend on the element position. As a result, the division of input current between compensating reactances and radiating elements is not necessarily the same for each element.

Two methods of measuring the ratio of radiating currents have been investigated:

(a) The input impedance of the complete aerial is measured. A small change is then made to the impedance of each dipole in turn by clamping an attachment of suitable form to the dipole limb. From the resulting changes to the input impedance it is possible to determine the radiating currents of the dipoles. This method will be called the 'impedance-perturbation method'.

(b) Small pick-up loops are attached to the limbs of each dipole, close to the drive point. The outputs from the loops are proportional to the radiating currents, and their complex ratio can be measured. This method will be called the 'probe method'.

*The folded dipole is, of course, an example of a dipole integrated with a parallel compensating reactance.

3.2. The Impedance-Perturbation Method

3.2.1. Principle of Method

Let the input impedance of a linear reciprocal network be Z_1. If a small impedance δZ_2 is inserted in a branch of the network carrying a current I_2, it is shown in the Appendix, Section 8.1., that:

$$I_2^2 = \frac{\delta Z_1}{\delta Z_2} \; I_1^2 \tag{1}$$

where I_1 is the input current before the perturbation is made, and δZ_1 is the resulting change in Z_1. This expression is valid provided the perturbing impedance δZ_2 is small compared with the impedance of the branch into which it is inserted.*

It follows from equation (1) that I_2 can be determined from the change in input impedance provided the input current and perturbing impedance are known. If the ratio between the currents flowing in two branches of a network is required, measurements of δZ_1 are made first with the perturbation in one branch, and then with the same perturbation in the other branch; the required current ratio is then equal to the square root of the ratio of the observed two values of δZ_1.

Similarly, if instead of inserting a series impedance an admittance δY_2 is connected between any two points in the network, it can be shown that for small values of δY_2:

$$V_2^2 = -\frac{\delta Z_1}{\delta Y_2} \; I_1^2 \tag{2}$$

where V_2 is the voltage between the two points.

Equations (1) and (2) can be used to determine the complex ratio of currents or voltages, provided suitable means be available for measuring small changes in impedance. Since a square root must be taken there is an ambiguity of 180° in the phase, but there is usually no doubt which value should be taken.

An error may arise since the 'perturbing' impedance δZ_2 must be made sufficiently large to avoid instrumental errors in measuring extremely small changes in impedance, but at the same time sufficiently small to make the approximations valid. The error depends not only on the value of δZ_2, but also on the total number of elements in the system, and the maximum current ratio to be measured. If, for instance, the number of elements is large, or the current in the perturbed element is small, a large value of δZ_2 may produce a value of δZ_1 which is so small as to be difficult to measure accurately. It is possible to determine theoretically the error arising from the use of a given value of δZ_2, provided the network constants are known. In practice, however, it is not always easy to assess the equivalent network for an aerial system; in doubtful cases it is therefore necessary to make several measurements with successively smaller values of δZ_2, in order to be certain that the error is sufficiently small. As discussed later in Section 4, the impedance-perturbation method has been used mainly in the small-scale model work.

* Strictly, δZ_2 must be such as not to change the ratio of the branch current I_2 to the input current I_1; this implies that $\delta Z_2 \ll Z_2$.

3.2.2. Instrumental Arrangement and Measurement Techniques

A model aerial may have many radiating elements. The change to the input impedance, δZ_1, of the complete aerial when the impedance of one element is perturbed by an amount δZ_2 is therefore very small. For example, if δZ_2 is 5% of the self-impedance of one radiating element and there are eight elements, the change of input impedance would be about 0·6%. Such a change would be almost imperceptible on an instrument set up to measure the input impedance directly. This difficulty is removed by the use of the arrangement shown in schematic form in Fig. 1.

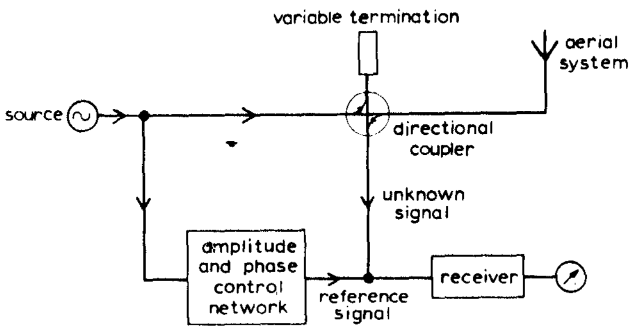

Fig. 1 - System for impedance-perturbation measurements

The aerial is fed viâ a directional coupler, and the amplitude and phase of the backward-wave output of the coupler is compared with a reference signal. (The system therefore measures changes in the reflexion coefficient of the aerial system, but, as shown in the Appendix, Section 8.1., this is equivalent to measuring changes in the input impedance.) The only purpose of the directional coupler is to improve the accuracy of the measuring system. The coupler need not have a high directivity,* and the aerial need not be well-matched, since the variable termination may be used to 'back-off' an initial output due to such imperfections.

The amplitude and phase control network in the reference signal path is used to provide a signal of equal amplitude, but opposite phase, to that which appears from the coupler when the impedance of the aerial is perturbed. In this way a null is produced at the receiver and the arrangement operates in the manner of a bridge network.

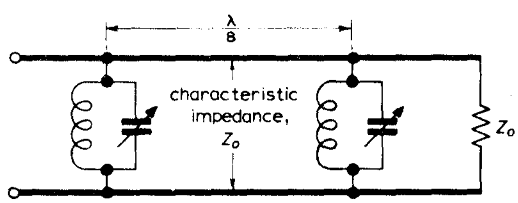

Fig. 2 - Circuit of variable termination

At u.h.f. a G.R. admittance meter forms a convenient amplitude and phase control for providing the reference signal; the technique of using this instrument for amplitude and phase measurement has been described.[2] The circuit of the variable termination device is shown in Fig. 2. Two tuned circuits are spaced $\lambda/8$ apart on a line of characteristic impedance Z_0; when the circuits are resonant the input impedance of the network is equal to Z_0. The variable capacitors of the tuned circuits provide controls of the modulus and phase of this impedance. These controls may therefore be set to reflect a signal of amplitude and phase such as to cancel the initial signal at the receiver arising from imperfections in the coupler as well as any mismatch at the aerial.

* The directivity is a measure of the imperfection of a directional coupler. It is defined as the ratio of forward-wave output to the backward-wave output when the main transmission path is perfectly matched.

In general there are two ways of applying the impedance-perturbation method to the measurement of dipole loop* *currents*. These are:

(a) *Parallel* perturbation, i.e. the addition of a susceptance at the tip of the dipole.

(b) *Series* perturbation, i.e. the insertion of a series impedance close to the drive point.

At first it was considered that, for dipoles having a given physical form, there would be a fixed relationship between the radiating current at the drive point and the radial electric intensity at or near the dipole tip. Perturbation of this electric intensity may be conveniently achieved by placing small dielectric disks at the tips of a dipole. For example, it was found that for a 500 Mc/s $\lambda/2$ dipole disks of polythene about 1 in (2·5 cm) diameter and ¼ in (0·63 cm) thick gave the right order of impedance perturbation. It was later realized, however, that this method of perturbation led to significant errors for the following reasons:

(i) The relationship between the radiating current at the drive point and the radial electric intensity at the dipole tip depends upon the drive-point impedance, even though the radiating elements are mechanically identical. It may be shown[3] that the current distribution on a half-wave dipole in the presence of other dipoles is given approximately by:

$$I(\theta) \quad \alpha \quad \sin\theta \left[1 - \frac{j}{Z_0}(R_R + Z_m)(1 - \tan\frac{\theta}{2})\right] \tag{3}$$

where θ = electrical distance from dipole tip

Z_0 = characteristic impedance of dipole limbs

R_R = radiation resistance of isolated dipole

Z_m = mutual impedance due to coupled dipoles, referred to the current loop.

The radial electric intensity at any point on a conductor carrying a current I is proportional to the rate of change of I with distance along the conductor. By differentiating equation (3) with regard to θ and putting $\theta = 0$, we obtain the following expression relating the electric intensity at the tip to the drive current:

$$E_{tip} \quad \alpha \quad \left\{1 - \frac{j}{Z_0}(R_R + Z_m)\right\} \tag{4}$$

In a typical multi-element aerial system consisting of dipoles carrying equal radiating currents, Z_0 is about 400 ohms, R_R about 70 ohms and the modulus of Z_m may vary from about $0{\cdot}2\ R_R$ to $0{\cdot}8\ R_R$. Equation (4) shows

* i.e. the current at the maximum of the approximately sinusoidal distribution; for $\lambda/2$ aerials carrying the same loop currents the radiated fields are also the same within close limits, even though the radiation resistance may differ appreciably.

that the associated errors in measuring a current ratio could be up to 30% in amplitude and 15° in phase. Errors of this order are improbable since they would be caused by unlikely values of Z_* (e.g. $+0{\cdot}8R_R$ in one dipole and $-0{\cdot}8R_R$ in another), but clearly E_{tip} is not an accurate guide to the drive current.

(ii) A second error arises because the addition of dielectric disks to the tips of a dipole modifies the current distribution along the dipole. This changes the coupling to other dipoles in the aerial, and hence the impedance of these dipoles; the change of input impedance to the complete aerial is then the result of the simultaneous perturbation of a number of dipoles rather than that of the single dipole. This effect is analysed in the Appendix, Section 8.2.; the error is comparable in magnitude with that described in (i) above.

It should be noted that these errors are independent of the value of the perturbing impedance, δZ_2. As already discussed, additional errors may nevertheless arise from the use of too large a value of δZ_2.

The errors described above do not occur if a *series* impedance perturbation is made, provided that the insertion of the series impedance close to the drive point does not change the overall length of the dipole. This is conveniently achieved by sliding a thin ferrite ring over the dipole. (In the case of folded dipoles the ferrite ring must enclose all the limbs in order to measure only the radiating currents.) By this means the desired perturbation of the radiating current is achieved directly and without any change to mutual impedances; the only possible error then is that due to the use of too large a value of δZ_2 and in practice this error can be made small.

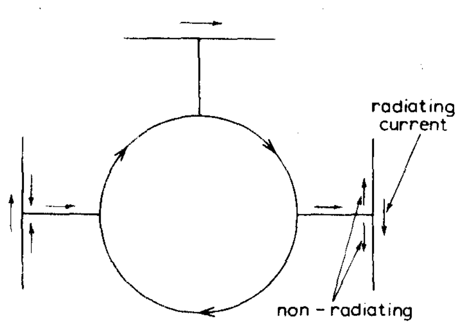

Fig. 3 - Currents flowing in a tier of three tangential dipoles

It is important that balanced* perturbations are used, since only the 'push-pull' current in the dipole must be measured. If only one perturbation is applied an error arises from possible non-radiating 'push-push' currents;† Fig. 3 illustrates how these currents arise in a system comprising tangential dipoles mounted on a cylindrical mast. The outer arrows on each dipole represent the prescribed 'push-pull' currents flowing in the dipoles; the inner arrows represent additional currents induced in the support booms of the two side dipoles by the central dipole. If the current in, say, only the right-hand limb of each dipole is measured (by either perturbation or by a pick-up loop) an error will occur in the case of the side dipoles, since the senses of the 'push-push' currents are opposed. Experience has shown that this effect can lead to an apparent asymmetry of the currents in the limbs of the tangential dipoles of the order of 50% in amplitude. A vertical dipole does not couple with the support booms of other dipoles in the same tier, but it may couple with other booms in the array. Even with an aerial system of vertical dipoles the effect may therefore still be appreciable.

*i.e. two equal perturbations, one being applied on each side of the dipole drive-point.

†Strictly speaking, the push-push currents also radiate, but only to a small extent for $\lambda/2$ dipoles.

In carrying out measurements we must first decide the approximate change in the reflexion coefficient it is necessary to measure. In a typical case (all elements carrying nominally equal currents) the change in reflexion coefficient $\delta\rho$, at the input to the aerial system is given by:

$$\delta\rho \simeq \frac{\delta Z_2}{2nZ_2} \qquad (5)$$

where Z_2 is the impedance of one radiating element

δZ_2 is the impedance perturbation,

n is the number of radiating elements.

There are relatively few aerials in use by the BBC which employ elements carrying unequal currents, and in these only two values of current ratio, 1 and k ($1 > k > 0{\cdot}5$), are involved. For systems of this type $\delta\rho$ is given by the following expressions:

$$\delta\rho \simeq \frac{\delta Z_2}{2Z_2} \; \frac{1}{(mk^2 + n)} \qquad (6)$$

where one out of n elements carrying unit current is perturbed, where $(m + n)$ is the total number of elements, and

$$\delta\rho \simeq \frac{\delta Z_2}{2Z_2} \; \frac{k^2}{(mk^2 + n)} \qquad (7)$$

when one out of m elements carrying a current k is perturbed.

Experience has shown that in a typical case the value of $\delta Z_2/Z_2$ can usually be as high as $0{\cdot}1$ before the errors inherent in the method become appreciable. Initial measurements are therefore made with the perturbing ferrite rings adjusted to give this order of impedance change.

To check the magnitude of the perturbations and the sensitivity of the measuring system, a small known change in the reflexion coefficient is made by replacing the aerial by an attenuator having the same characteristic impedance as the line feeding the aerial; the attenuator is first matched, and then terminated by a short circuit. (To achieve a balance an attenuator may be required in the reference signal path.) For $\delta Z_2/Z_2 = 0{\cdot}1$, and equal currents in all elements, the calibration attenuator will have a value given by:

$$\alpha(\text{dB}) = 10 \log_{10} 20n \qquad (8)$$

A second set of measurements is then made with a smaller value of $\delta Z_2/Z_2$ (say, $0{\cdot}05$) and the results compared with those of the initial measurements. If these results are not in reasonable agreement it may be necessary to repeat measurements with a further reduction in $\delta Z_2/Z_2$. If the amplitude and phase controls are not sufficiently sensitive the network must be modified until satisfactory readings are obtained.

The smallest value of $\delta Z_2/Z_2$ which can be used is limited by the *stability* of the measuring system, i.e. the constancy of measured results for a fixed condition of the aerial under test. The following requirements are of importance:

(i) The environment must be stable. For example, it has been found that people moving at a distance of about 50 ft (15 m) from a 500 Mc/s model can significantly affect readings. In addition, all connexions in the apparatus must be reliable to an unusual degree. To avoid possible trouble it is advisable regularly to clean plugs and sockets, and to check soldered joints.

(ii) Stray pick-up in the measuring apparatus due to radiation from the aerial must be avoided. This can be reduced by arranging that a minimum in the radiation pattern of the aerial is directed towards the apparatus. A further reduction (equal to the output ratio of the directional coupler) can be achieved with no disadvantage by interchanging the connexions to the aerial and the variable termination.*

(iii) The frequency stability of the source is important; for u.h.f. work it is necessary to have a source stable to within about 100 kc/s over a period of several hours. To reduce the frequency-sensitivity of the system the electrical lengths of the cables from the directional coupler to the aerial and to the variable termination should be approximately equal. As a further safeguard against error, these cables should be of the same type, and as far as possible, should be arranged so that they are subjected to the same temperature changes. Experience has shown that when a u.h.f. model is removed from indoors in preparation for perturbation measurements, a period of about one hour must elapse before temperature conditions are sufficiently stable to permit accurate measurements.

It may be necessary to repeat measurements several times to obtain a 'statistical mean' result. If there are more than about ten radiating elements, errors of the type described above may make it difficult to obtain satisfactory results when one element at a time is perturbed. A possible solution then is to perturb a number of elements simultaneously as described in the Appendix, Section 8.3.; by this means, provided the element currents are nominally equal, the aggregate radiating current may be determined. Hence, if the aggregate radiating current is measured for all the elements on each bearing, the effective current ratios of the elements in the equivalent single tier of the aerial may be found.

3.3. The Probe Method

As discussed in Section 4, the impedance-perturbation method was found to be impracticable when applied to full-scale aerials. It was therefore necessary to determine the requirements of the alternative probe system.

3.3.1. Principle of Method

A small pick-up loop is mounted near to the dipole drive-point and serves as a probe to sample the radiating current. To reproduce the model measurements

*This is in fact the usual practical arrangement. That in Fig. 1 is shown mainly because it is simpler to envisage.

exactly, the loop should sample the current at the same point as the series-impedance perturbation on the small-scale aerial model; this would require the loop to be very close to the drive point. The loop must, however, be sufficiently far from the drive point to be uninfluenced by the magnetic field associated with any compensating stub. There is then the possibility of an error because the current distribution on a radiating element is dependent upon the degree of mutual coupling with other elements, so that the current at the probe position may differ from that at the drive point, the ratio depending on the mutual coupling. The order of the error may be determined from equation (3) in Section 3.2.2. which gives the current distribution on a half-wave dipole. When $\theta = 90°$, i.e. at the drive point, equation (3) shows that the term involving Z_m is zero, but when θ is less than 90°, $I(\theta)$ is modified by Z_m. In a typical multi-element aerial system Z_m may be as high as $0{\cdot}8R_R$ for some elements; assuming θ to be 75°, $I(\theta)$ could then be about 4% different in amplitude, or 3° in phase, from the case when $Z_m = 0$. This error is acceptable, bearing in mind that this is an extreme example. Provided that the conditions described in Section 3.3.2. are satisfied in setting up a probe measuring system, the effect described above is the only inherent source of error.

3.3.2. Instrumental Arrangement

The basic system for measuring radiating currents by the probe method is shown in Fig. 4; it is very similar to that used for the impedance-perturbation method. In Fig. 4, however, the amplitude and phase-control network in the reference signal path merely provides a signal of equal amplitude but opposite phase to that derived from the current-sampling probe, and its readings are therefore directly proportional to the aerial radiating currents. To reduce the frequency-sensitivity of the arrangement the path length l_3 is made equal to $l_1 + l_2$ (which may be 20 to 30λ in a typical case).

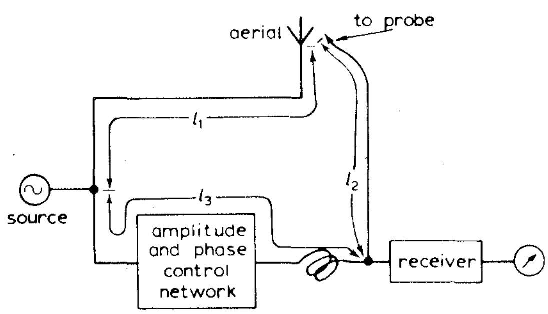

Fig. 4 - System for probe measurements

As already stated, the degree of coupling of the loop to the radiating element must be sufficiently close to avoid the effects of stray pick-up in the measuring apparatus. On the other hand, if the coupling is too great the impedance of the radiating element may be significantly disturbed. For typical Band I and Band II aerials a dipole-to-probe current ratio in the range 30 to 40 dB has been found to be a suitable compromise between these conflicting requirements. In practice it is convenient to clamp the measuring loop directly on to the limb of a dipole, and to achieve the small degree of coupling required by using a loop having an area of the order of 1 in^2 (6 cm^2).

Since the loops are used only during the initial setting up of an aerial they are not required to be built as a permanent feature into each radiating element. A form of loop has therefore been developed which can be readily attached to the elements in an already-erected aerial system. This is shown in Fig. 5; Fig. 6 shows two such loops in position on a dipole. Two loops are necessary to avoid errors due to non-radiating 'push-push' currents (see Section 3.2.2.). Connexion is made to each loop by means of a small diameter coaxial cable, from which the

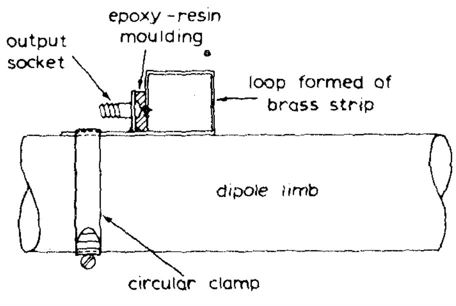

Fig. 5 - General arrangement of measuring loop

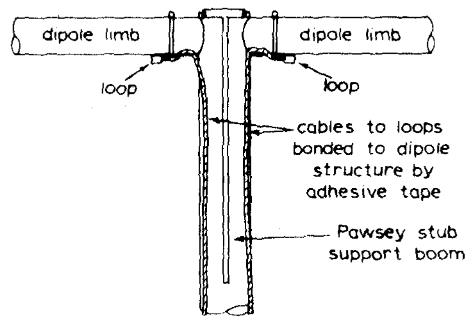

Fig. 6 - Dipole fitted with measuring loops

insulating sheath has been stripped to expose the braided-copper outer. The cable is held in close contact with the dipole structure up to the point where it enters the support mast interior, by adhesive tape applied at short intervals. To minimize the difficulty of equalizing lengths the loop cables are as short as possible, and are terminated just inside the support mast. Measurements using equipment at ground level are then carried out by means of a single long downlead which is plugged to each loop cable in turn.

With loops mounted as shown in Fig. 6 the outputs due to the radiating currents proper are in antiphase, whilst the outputs due to possible non-radiating 'push-push' currents are in phase. By measuring each loop output in turn, and calculating the vector difference, the unwanted 'push-push' component is eliminated. A better electrical arrangement might be obtained if the sense of one loop were reversed. The outputs due to the radiating current would then be in phase, and similar readings would be obtained on the measuring bridge from each loop, thus reducing possible errors due to inaccuracy in the bridge. A further advantage would be that any unwanted components in the outputs associated with the drive voltage of the dipole together with the 'push-push' current components previously mentioned are eliminated by vector addition of the outputs. This system has not been adopted, however, since it was felt that the advantages could be outweighed by errors arising from the necessary mechanical asymmetry of the loops and associated cables.

In the case of folded dipoles, a complication arises in deciding the position of the current-sampling loops, since both radiating and non-radiating components of current flow in each limb. The loops cannot be clamped to one limb on each side of the drive point since the outputs would then be proportional to both components of current. They must therefore be placed so as to be coupled only to the radiating current. If the folded dipole has two limbs of equal diameter this is achieved by placing the loops at the positions shown in Fig. 7, which also shows the magnetic field configurations corresponding to each component of current. The wanted output from the 'push-push' radiating current is a maximum when the loop is spaced a distance d from the line joining the centres of the limbs, where $2d$ is the spacing between the centres.

If the limbs are of unequal diameter, or there are more than two limbs, the correct position of the loop is best ascertained by plotting the magnetic field.

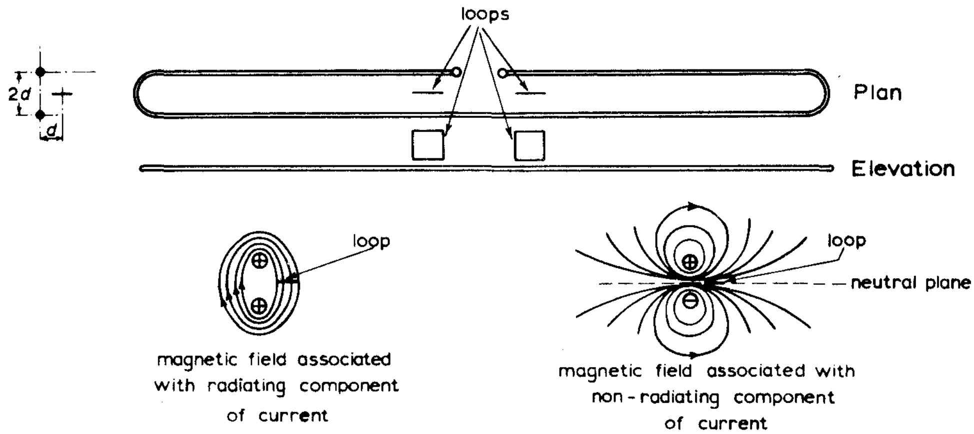

Fig. 7 - Disposition of current-measuring loops on symmetrical two-limb folded dipole

3.4. Bridge for Measuring Current Ratios and Impedance Ratios

A special bridge was developed for measurements (either by the perturbation or probe method) on full-scale v.h.f. aerials. It measures the current in terms of two components (an in-phase and a quadrature component relative to a reference signal).

The circuit diagram is shown in Fig. 8; the source feeds a hybrid transformer supplying a reference signal proportional to that delivered to the aerial. This reference signal is attenuated by a calibrated tapped inductance, which determines the sensitivity of the bridge, and is then applied to a resistor and capacitor in parallel. The capacitor is variable, the control being calibrated in frequency, so that the reactance of the capacitor can be made equal to the resistance at the operating frequency. The currents in the two paths return to earth through two 10-turn Helitrans[4] and a combining transformer, the secondary of which also carries the signal returning from the aerial. The Helitrans can be set to multiply either the resistive or reactive currents by a factor lying between +1 and -1. When adjusted for zero output from the secondary, as indicated by the detector, the currents in the combining transformer balance; at the same time the zero voltage across the transformer ensures that the currents injected by the resistor and capacitor before

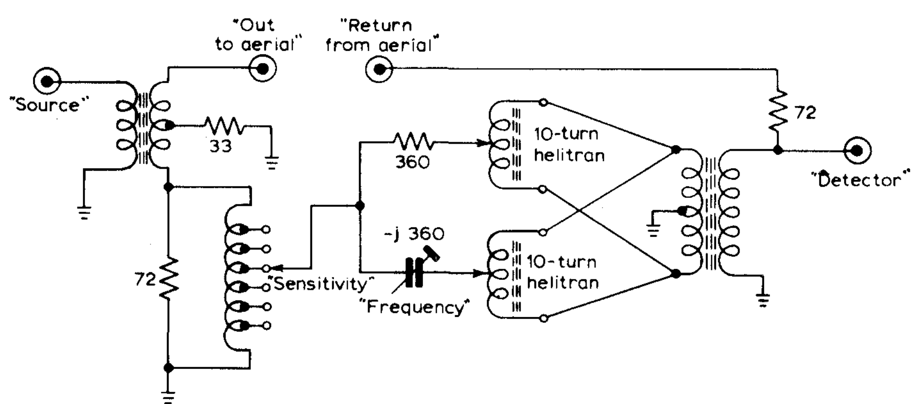

Fig. 8 - Circuit of v.h.f. complex transfer-coefficient bridge

division are equal in magnitude and in phase quadrature. The Helitran controls are calibrated to indicate the magnitude and signs of the real and imaginary parts of the return signal in terms of the reference signal.

4. DISCUSSION

Radiating current measurements were required initially on small-scale model aerials; for this application it was decided to concentrate attention on the impedance-perturbation method, for the following reasons:

(a) The perturbation method may be applied readily to different types of radiating element. With the probe system it was thought that it might be necessary to produce suitable current-sensitive loops for each type of radiating element (e.g. simple dipole or folded dipole).

(b) In view of the small size of the model aerials, it was thought that instrumental difficulties would arise in making the probe method satisfactory. For example, great care would be required to ensure that the probes and cables were electrically identical.

In the case of full-scale aerials trial measurements showed that the use of the perturbation method was inconvenient. The application and removal of the perturbing attachments involved hoisting and lowering a rigger many times to obtain one set of current ratio measurements at one frequency. To avoid affecting the aerial impedance it was essential when readings were taken for the rigger to be either at ground level or within the screening of the mast, and for the hoisting ropes to be lashed in a fixed position. This procedure was found to be unacceptably time-consuming and laborious, and errors arose due to the appreciable time interval between readings. It was consequently necessary to repeat measurements in order to reduce 'scatter' on results due to the inevitable 'drift' of the type previously mentioned. Experimental measurements were, however, made on aerials equipped by the contractor with current-measurement probes, so enabling a useful comparison to be made between the two methods of measurement. As a result it was decided that the probe system was sufficiently accurate, and more practicable for measurements on full-scale aerials.

5. CONCLUSIONS

Two methods of measuring complex radiating current ratios in aerial systems are described. Errors can arise in the impedance-perturbation method unless the perturbation is achieved by a small series impedance placed close to the drive point of the radiating element. This method has nevertheless proved to be impracticable when applied to full-scale aerials, since the application and removal of the perturbing attachments is time-consuming and laborious. It may, however, be readily applied to measurements on small-scale models. The alternative method of using current-sampling probes attached to the radiating elements is suitable for full-scale aerials, but because of the mechanical difficulties associated with producing small probe measuring systems it is not favoured for model work. An overall measurement accuracy of the order of 5% in amplitude and 5° in phase has been achieved for both methods.

6. ACKNOWLEDGEMENTS

The impedance-perturbation method of radiating current measurement was suggested by Mr. G.D. Monteath and further theoretical contributions were made by Mr. W. Wharton, Mr. P. Knight and Dr. J.B. Izatt. Mr. G.H. Millard, Mr. A. Brown and Mr. R.D.C. Thoday were concerned in establishing practical measuring systems. Mr. R.V. Harvey and Mr. M.W. Greenway were responsible for the development of the v.h.f. complex transfer coefficient bridge.

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8. APPENDIX: THE PERTURBATION METHOD OF CURRENT OR VOLTAGE MEASUREMENT

8.1. Theoretical Basis

In this method the current flowing in a branch of a linear reciprocal network is determined by measuring the change in input impedance which occurs when a small change is made to the impedance of the branch.

Fig. 9 shows the representation of a network driven by a generator of e.m.f. V_1. The impedance Z_2, which carries a current I_2, represents any branch of the network.

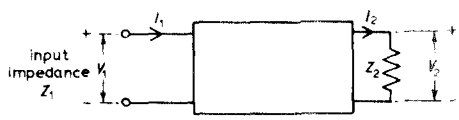

Fig. 9 - Voltage and current conventions in a linear reciprocal network

The behaviour of the network may be described by the equations

$$V_1 = aV_2 + bI_2 \tag{9}$$

$$I_1 = cV_2 + dI_2 \tag{10}$$

where a, b, c and d are complex quantities, related by the expression

$$ad - bc = 1 \tag{11}$$

The input impedance is therefore

$$Z_1 = \frac{V_1}{I_1} = \frac{aV_2 + bI_2}{cV_2 + dI_2} = \frac{aZ_2 + b}{cZ_2 + d} \tag{12}$$

If a small change δZ_2 is made to the impedance Z_2, the change in input impedance is

$$\delta Z_1 = \frac{dZ_1}{dZ_2}\,\delta Z_2 = \frac{ad - bc}{(cZ_2 + d)^2}\,\delta Z_2 = \frac{\delta Z_2}{(cZ_2 + d)^2} \tag{13}$$

From equation (10) we have

$$\frac{I_1}{I_2} = cZ_2 + d \tag{14}$$

Substituting in (13) gives the result*

$$\delta Z_1 = \left(\frac{I_2}{I_1}\right)^2 \delta Z_2 \tag{15}$$

*If the change of impedance is not small it may be shown that $\delta Z_1 = (I_2 I_2'/I_1 I_1')\delta Z_2$ where I_1' and I_2' are the currents flowing in Z_1 and Z_2 respectively after perturbation.

Transposing equation (15) we obtain

$$I_2^2 = \frac{\delta Z_1}{\delta Z_2} I_1^2 \tag{16}$$

which is the equation upon which the perturbation method of current measurement is based. The branch current I_2 may be determined from δZ_1 if δZ_2 and I_1 are known. Alternatively, currents in different branches may be compared by inserting the same impedance δZ_2 in each branch in turn; the values of I_1 and δZ_2 do not then need to be known.

Currents may also be measured or compared by measuring changes in input admittance (δY_1) rather than impedance, since it may also be shown from equations (9) and (10) that

$$I_2^2 = \frac{\delta Y_1}{\delta Z_2} V_1^2 \quad \text{as } \delta Z_2 \to 0 \tag{17}$$

In practice it may be more convenient to measure changes in reflexion coefficient rather than changes of impedance or admittance. The reflexion coefficient of the network before perturbation is

$$\rho = \frac{Z_0 - Z_1}{Z_0 + Z_1} \tag{18}$$

where Z_0 is the characteristic impedance of the measuring system.

The change in reflexion coefficient due to perturbation is therefore

$$\delta\rho = \frac{d\rho}{dZ_1} \delta Z_1 = \frac{-2Z_0 \, \delta Z_1}{(Z_0 + Z_1)^2} \tag{19}$$

Since Z_0 and Z_1 are constant, $\delta\rho$ is proportional to δZ_1.

The perturbation method may also be used to measure and compare the voltages existing across the terminals of a network. A small shunt admittance δY_2 is connected across the terminals; the resulting changes in input impedance and admittance are given respectively by the expressions

$$\delta Z_1 = -\left(\frac{V_2}{I_1}\right)^2 \delta Y_2 \tag{20}$$

$$\delta Y_1 = \left(\frac{V_2}{V_1}\right)^2 \delta Y_2 \tag{21}$$

8.2. Errors caused by Mutual Coupling

The perturbation method of current or voltage measurement is liable to errors if there is mutual coupling between the branches of the network whose currents or voltages are being measured. As will be shown later, the addition of a perturbation to a branch being measured may cause the impedance of other branches to change; the resulting change of input impedance is then the result of the simultaneous perturbation of a number of branches.

In order to assess the order of magnitude of the resulting errors it is first necessary to consider the effect of a number of simultaneous perturbations. It has been shown in Section 8.1. that if the impedance of a branch is changed by δZ_2 the change in input impedance is $(I_2/I_1)^2 \delta Z_2$ where I_1 is the input current and I_2 the branch current. If an additional change δZ_r is now made to another branch carrying a current I_r, the input impedance will undergo a further change of $(I_r/I_1)^2 \delta Z_r$. In general, if a number of branches ($2, 3 \ldots r \ldots n$) undergo simultaneous impedance changes, the total impedance change at the input terminals will be

$$\delta Z_1 = \frac{1}{I_1^2} \sum_{r=2}^{r=n} I_r^2 \, \delta Z_r \tag{22}$$

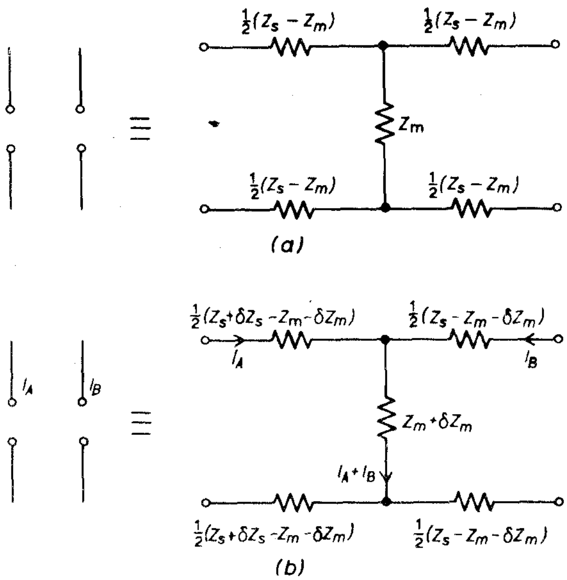

Fig. 10 - Equivalent circuit of coupled dipoles

(a) before perturbation
(b) after perturbation

We will consider now a two-branch network with mutual impedance between branches; a familiar example of such a network is a pair of identical dipoles, whose equivalent circuit before perturbation is shown in Fig. 10(a). If the impedance of the left-hand dipole is increased to $Z_s + \delta Z_s$ by an addition to its length the mutual impedance will increase to, say, $Z_m + \delta Z_m$.* The equivalent circuit is then as shown in Fig. 10(b). Suppose that currents I_A and I_B flow in the left-hand and right-hand dipoles respectively. Since simultaneous impedance changes have been made in three arms of the equivalent network the total input impedance change, from equation (22), is

$$\delta Z_1 = \frac{1}{I_1^2}\left[I_A^2 \, (\delta Z_s - \delta Z_M) - I_B^2 \, \delta Z_M + (I_A + I_B)^2 \, \delta Z_M\right]$$

$$= \frac{1}{I_1^2}\left[I_A^2 \, \delta Z_s + 2 I_A I_B \delta Z_M\right] \tag{23}$$

From mutual impedance tables for dipoles of different length† we may determine a factor k given by

$$k = \frac{\delta Z_M}{\delta Z_s} \tag{24}$$

*The physical significance of this increase of Z_M can be understood by considering the current distribution on the left-hand dipole. If the input current remains constant the increased length results in a greater field strength at the right-hand dipole and increased coupling. This result still applies if pure dielectrics are placed at the ends of the left-hand dipole, since these behave like capacity tops and also modify the current distribution.

†See, for example, tables in 'The Theory of Linear Antennas' by Ronald King. The values of δZ_m derived from these tables must be halved in calculating k, since we are increasing the length of one dipole only, not two as in the tables.

Equation (23) may now be written

$$\delta Z_1 = \frac{1}{I_1^2}\left[I_A^2 + 2k\ I_A I_B\right]\ \delta Z, \tag{25}$$

Thus δZ_1 is proportional to I_A^2 only when $k = 0$ or $I_B = 0$.

Suppose that an attempt is made to measure the current ratio I_A/I_B by making identical impedance changes to the two dipoles in turn. Let the measured impedance changes be δZ_{1A} and δZ_{1B} respectively. Then if $k = 0$.

$$\delta Z_{1A}/\delta Z_{1B} = I_A^2/I_B^2 \tag{26}$$

and the current ratio is measured correctly.

When k is not zero, from equation (25) we have

$$\frac{\delta Z_{1A}}{\delta Z_{1B}} = \frac{I_A^2 + 2k\ I_A I_B}{I_B^2 + 2k\ I_A I_B} \tag{27}$$

There is no error in this case if $I_A = \pm\ I_B$. In general, however, the impedance-change ratio does not give the current ratio correctly. The magnitude of the error depends on the current ratio and on the mutual impedance change; for example, for parallel $\lambda/2$ dipoles spaced $\lambda/2$ apart and carrying currents whose amplitudes are in the ratio 2 : 1, the error may be as much as 20% in amplitude or 15° in phase, depending upon the relative phase of the dipole currents.

The presence of mutual impedance between the branches of a network does not necessarily mean that errors will occur when the perturbation method is used. Provided the perturbations can be applied without any change in the mutual impedance taking place, no error will result. This is equivalent to making the factor k of equation (24) zero. This may be achieved in the case of dipoles by placing the series impedance at the base of the dipole arms, care being taken to ensure that the overall length of the dipole remains unchanged. The most convenient way of doing this on model aerials is to place ferrite rings over the dipole arms.

8.3. Simultaneous Perturbations to a Number of Aerial Elements

In the case of an aerial system containing a large number of radiating elements it may be necessary to perturb simultaneously a group of elements, carrying nominally-equal currents, in order to obtain an input-impedance change sufficiently large for accurate measurement. In Section 8.2. it was shown that the total impedance change at the input of a network due to simultaneous impedance changes in a number of branches (2, 3...r...n) would be given by:

$$\delta Z_1 = \frac{1}{I_1^2}\sum_{r=2}^{r=n} I_r^2\ \delta Z_r \tag{28}$$

If the same impedance perturbation δZ_2 is introduced in each branch the input impedance change is

$$\delta Z_1 = \frac{\delta Z_2}{I_1^2} \sum_{r=2}^{r=n} I_r^2 \tag{29}$$

Suppose the currents being measured simultaneously are I_a, I_b, I_c ... We wish to determine the aggregate current, i.e. $[I_a + I_b + I_c \ldots]$ If these currents are all nominally I_0 but have actual values of $I_a = I_0 + \delta I_a$, etc., then:

$$\sum I_r^2 \simeq (I_0^2 + 2I_0\, \delta I_a) + (I_0^2 + 2I_0\, \delta I_b) + \ldots$$

$$= nI_0^2 + 2I_0 \sum \delta I_r \text{ provided } \delta I_r/I_r \text{ is small (say less than 0·1)}$$

where n is the number of branches being simultaneously perturbed.

Taking the square root we have:

$$\left[\sum I_r^2\right]^{1/2} = \left[nI_0^2 + 2I_0 \sum \delta I_r\right]^{1/2} = \frac{1}{\sqrt{n}}\left[nI_0 + \sum \delta I_r\right] \tag{30}$$

provided that

$$\sum \delta I_r \ll nI_0$$

This is the apparent current measured. The required current is

$$I_{\text{aggregate}} = \sum I_r = \left[I_0 + \delta I_a + I_0 + \delta I_b + \ldots\right] = nI_0 + \sum \delta I_r$$

We therefore have

$$I_{\text{aggregate}} = I_{\text{measured}} \times \sqrt{n} \tag{31}$$

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